Cobalt Recycling in the United States in 1998

By Kim B. Shedd

U.S. GEOLOGICAL SURVEY CIRCULAR 1196–M

FLOW STUDIES FOR RECYCLING METAL COMMODITIES IN THE UNITED STATES

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
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FOREWORD

As world population increases and the world economy expands, so does the demand for natural resources. An accurate assessment of the Nation's mineral resources must include not only the resources available in the ground but also those that become available through recycling. Supplying this information to decisionmakers is an essential part of the USGS commitment to providing the science that society needs to meet natural resource and environmental challenges.

The U.S. Geological Survey is authorized by Congress to collect, analyze, and disseminate data on the domestic and international supply of and demand for minerals essential to the U.S. economy and national security. This information on mineral occurrence, production, use, and recycling helps policymakers manage resources wisely.

USGS Circular 1196, "Flow Studies for Recycling Metal Commodities in the United States," presents the results of flow studies for recycling 26 metal commodities, from aluminum to zinc. These metals are a key component of the U.S. economy. Overall, recycling accounts for more than half of the U.S. metal supply by weight and roughly 40 percent by value.

Charles G. Groat
Director

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TABLE

CONVERSION FACTORS

Multiply	By	To obtain
metric ton (t, 1,000 kg)	1.102	short ton (2,000 pounds)
million metric tons (Mt)	1,102,000	short ton

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ABSTRACT

This report, which is one of a series of reports on metals recycling, defines and quantifies the 1998 flow of cobalt-bearing materials in the United States from imports and stock releases through consumption and disposition with particular emphasis on the recycling of industrial scrap (new scrap) and used products (old scrap). Because of cobalt's many diverse uses, numerous types of scrap were available for recycling by a wide variety of processes. In 1998, an estimated 32 percent of U.S. cobalt supply was derived from scrap. The ratio of cobalt consumed from new scrap to that from old scrap was estimated to be 50:50. Of all the cobalt in old scrap available for recycling, an estimated 68 percent was either consumed in the United States or exported to be recycled.

INTRODUCTION

The purpose of this report is to define and quantify the recycling[1] of cobalt-bearing scrap, which represents an important component of total cobalt supply. Figure 1 illustrates the flow of cobalt in 1998. It shows sources and distribution of U.S. cobalt supply with particular emphasis on the flow of cobalt-bearing scrap. Table 1 lists salient cobalt scrap statistics for 1998.

Cobalt is a silvery gray metal with many diverse uses that result from several of its unique properties—it has a high melting point, is ferromagnetic and retains its ferromagnetism at the highest temperature of any metal, is multivalent, and produces intense blue colors in conjunction with silica.

GLOBAL GEOLOGIC OCCURRENCE OF COBALT

The average concentration of cobalt in the Earth's crust is estimated to be approximately 0.002 percent. It is present in a large number of distinct mineral species, which include arsenides, hydrates, oxides, sulfarsenides, and sulfides. Most economically important terrestrial cobalt-bearing ore deposits can be classified as one of the following types: hydrothermal, lateritic nickel, magmatic nickel, or sediment-hosted (stratiform) copper. In addition to terrestrial deposits, large resources of cobalt are present in metal-rich nodules

and crusts on the ocean floor (Young, 1960, p. 12–15; Vhay and others, 1973, p. 145–150; Crockett and others, 1987, p. 6–7; and Alcock, 1988, p. 70–73, 78–81, 84–85).

Hydrothermal deposits form when cobalt minerals are precipitated from hot aqueous solutions into fractures or other openings or in place of preexisting minerals. Cobalt arsenides and sulfarsenides, such as cobaltite, skutterudite, and smaltite, are characteristic minerals of hydrothermal cobalt deposits (Young, 1960, p. 14, 16–17, 18, 22, 24; Vhay and others, 1973, p. 149–150; and Crockett and others, 1987, p. 7).

Laterites are soils formed over large areas of low relief by atmospheric weathering of sulfide and silicate ore minerals usually in hot and humid subtropical to tropical climates. Compared with the original unweathered rock, lateritic soils formed from ultramafic igneous rocks and their serpentinized derivatives are enriched in iron, nickel, cobalt, and other minor constituents. The nickel and cobalt minerals formed by this weathering include various complex carbonates, oxides, and hydroxides. Absolite, which is a mixture of cobalt and manganese oxides, is one example (Young, 1960, p. 14–16, 18, 25; Vhay and others, 1973, p. 148; Crockett and others, 1987, p. 7; Alcock, 1988, p. 78–81; and Burger, 1995, p. 1, 12, 14).

Magmatic ore deposits are formed when an immiscible sulfide liquid separates from and concentrates within a cooling and crystallizing mass of molten rock. This can occur above ground in lava flows or underground in intrusions of molten rock. In magmatic ore deposits, cobalt is concentrated along with nickel and iron in such sulfide minerals as pentlandite and pyrrhotite (Young, 1960, p. 12–16; Vhay and others, 1973, p. 146–147; Crockett and others, 1987, p. 6–7; and Alcock, 1988, p. 70–73).

Sediment-hosted copper deposits are also called stratabound or stratiform deposits. These deposits are copper-rich layers in sedimentary rocks. Some sediment-hosted copper deposits have been upgraded by supergene (weathering) processes. The cobalt-bearing minerals in unweathered rocks of these deposits include such sulfides as linnaeite and carrolite; oxides, such as heterogenite, are present in the weathered rocks (Young, 1960, p. 15–19, 21–22; Vhay and others, 1973, p. 150; and Crockett and others, 1987, p. 7).

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[1]Definitions for selected words are found in the Appendix.

DISTRIBUTION OF DOMESTIC COBALT SUPPLY

Exports of cobalt metal and compounds

Apparent supply of cobalt for fabrication
11,900

Home scrap
NA

Processing losses
350

New (prompt) scrap generated
2,280

New scrap exports
900

Cobalt products to U.S. market
9,270

Dissipative uses
2,000

Cobalt products reservoir
net change +3,770

DOMESTIC SUPPLY OF UNWROUGHT PRIMARY AND SECONDARY COBALT

Release of industry and Goverment stocks of cobalt metal and compounds
2,350

Imports of cobalt metal and compounds
7,670

Domestic production of cobalt metal powder and compounds

Home scrap
20

Processing losses
15

Old scrap generated:
Cemented carbide parts...700
Magnets.................700
Spent catalysts............600
Superalloy parts..........1,100
Other metal products......400
Total.................3,500

Old scrap imports
300

Old scrap stock decrease
25

Old scrap supply
3,830

Old scrap exports
900

Unrecovered old scrap
1,230

Old scrap consumed
1,700

New (prompt) scrap consumed
1,700

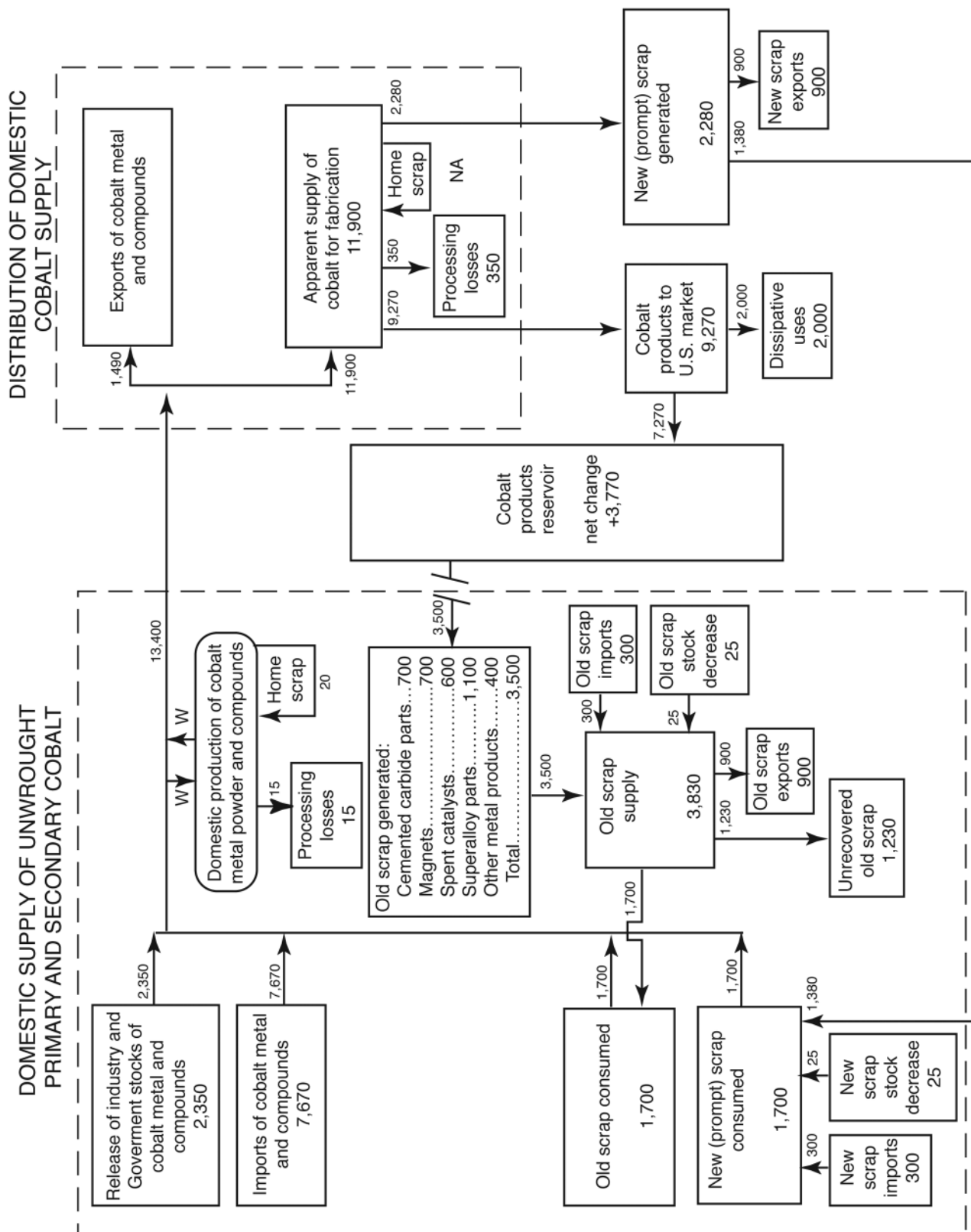New scrap stock decrease
25

New scrap imports
300

Figure 1. U.S. cobalt materials flow in 1998. Values are in metric tons of contained cobalt, are rounded to no more than three significant digits, and may not add to totals shown. NA, not available; W, withheld to avoid disclosing company proprietary data.

Table 1. Salient statistics for U.S. cobalt scrap in 1998. [Values in metric tons of contained cobalt, unless otherwise specified]

Old scrap:

    Generated[1] 3,500

    Consumed[2] 1,700

    Consumption value[3] . . . . $40 million

    Recycling efficiency[4] . . . . 68 percent

    Supply[5] 3,830

    Unrecovered[6] 1,230

New scrap consumed[7] 1,700

New-to-old-scrap ratio[8] 50:50

Recycling rate[9] . . . . 32 percent

U.S. net exports of scrap[10] 1,200

Value of U.S. net exports of scrap[11] . . . . $40 million

[1]Old scrap generated is estimated to have been the cobalt content of products theoretically becoming obsolete in the United States in 1998.

[2]Old scrap consumed is estimated to have been the cobalt content of used products that were recycled in 1998.

[3]Value of cobalt contained in old scrap, which was based on estimated quantities and values of the various types of cobalt scrap consumed.

[4]Recycling efficiency is (old scrap consumed plus old scrap exported) divided by (old scrap generated plus old scrap imported plus any old scrap stock decrease or minus any old scrap stock increase).

[5]Old scrap supply is old scrap generated plus old scrap imported plus old scrap stock decrease.

[6]Old scrap unrecovered is old scrap supply minus old scrap consumed minus old scrap exported minus old scrap stock increase.

[7]New scrap consumption includes prompt industrial scrap but excludes home scrap.

[8]New-to-old-scrap ratio is the ratio of quantities consumed, expressed as a percentage.

[9]Recycling rate is the fraction of the apparent cobalt supply that is scrap, on an annual basis. It is defined as (consumption of old plus consumption of new scrap) divided by apparent supply (see Appendix); measured in weight and expressed as a percentage.

[10]Net exports of scrap are cobalt contained in exports minus cobalt contained in imports of scrap. Trade in cobalt-bearing scrap is assumed to be 50 percent new scrap and 50 percent old scrap.

[11]Estimated unit value for net exports is greater than that for old scrap consumed because of the mix of scrap types assumed to be exported, imported, and consumed.

In 1998, the United States produced only negligible amounts of byproduct cobalt from its mining operations and had no production where cobalt was the primary commodity. The principal countries where cobalt was mined were Australia, Canada, Cuba, the Democratic Republic of the Congo [Congo (Kinshasa)], New Caledonia, Russia, and Zambia (Shedd, 2001, p. 20.17). Cobalt mined in Congo (Kinshasa) and Zambia was as a byproduct of copper from sediment-hosted deposits. Cobalt mine production from most other countries was as a byproduct of nickel. Cuban and New Caledonian production was from lateritic deposits. Canadian and most of the Russian production was from sulfide deposits. Production from Australia was from lateritic and sulfide deposits. Only in Morocco was cobalt produced as the primary commodity from a mining operation; the deposits in Morocco are hydrothermal in origin.

COBALT PRODUCTION PROCESSES

Cobalt-bearing ores are mined by conventional underground or open pit methods. They are processed by a wide variety of extractive metallurgical techniques depending on the type of ore, the availability of energy, environmental concerns, market demand for primary products and byproducts, and overall project economics. Nickel laterite ores are usually processed directly. Most other cobalt-bearing ores are first beneficiated, either by mineral flotation or gravimetric methods, to produce a mineral concentrate (De Cuyper, 1988, p. 206). Some ores and concentrates are roasted or smelted to a material referred to as "matte" prior to refining. Most cobalt-producing refineries use hydrometallurgical methods to extract the desirable metals from the ores, concentrates, or mattes and to separate cobalt from the other metals present in the resulting solutions (Kerfoot and Weir, 1988, p. 256). Some refineries also process scrap and cobalt intermediates, such as alloys, impure cobalt compounds, mixed metal sulfides, residues, and slags. Depending on the final processing steps, refined cobalt can be in the form of cobalt metal (cathode, granules, or ingot), metal powder (loose or briquetted), or cobalt chemicals (acetates, carbonate, chlorides, hydroxides, nitrates, oxides, or sulfates).

USES

U.S. cobalt consumption in 1998 can be divided into the following end-use categories: superalloys (44 percent); chemical compounds for a variety of applications (31 percent); cemented carbides and diamond tools (9 percent); magnetic alloys (8 percent); and specialty steels, other alloys, and other metallic uses (8 percent) (Shedd, 2001, p. 20.12). Superalloys are alloys developed for high-temperature service where relatively high mechanical stress is encountered and where surface stability is frequently required. Cobalt-bearing magnetic alloys include permanent magnetic alloys, such as alnico, samarium-cobalt, and iron-neodymium-boron, and soft magnetic alloys, such as permendur. Cobalt-bearing steels include high-speed steels from which cutting tools are made and maraging steels, which are characterized by their strength and workability. Other cobalt-bearing alloys are characterized by their resistance to corrosion and/or wear or by their controlled expansion.

Cemented carbides, which are also referred to as "hardmetals," are sintered powder metallurgical parts used as cutting tools and wear-resistant components by the metalworking, mining, oil drilling, and construction industries. In making these parts, cobalt metal powder is used as a binder to hold together the tungsten carbide grains. Diamond tools are similar to cemented carbides in that cobalt is used as a

binding agent to hold together wear-resistant particles, which, in this case, are diamonds. Saws for cutting non-metallic materials, such as stone and concrete, are essentially steel wheels with diamond-bonded segments attached to their circumference. The segments are made by blending, pressing, and sintering a mix of diamonds and cobalt metal powder. Diamond polishing wheels for grinding gem-quality diamonds are made by impregnating diamonds into a surface layer of cobalt on a steel wheel (Cobalt Development Institute, 1993; 2001, p. 83–84).

Applications for cobalt chemical compounds include animal feed additives, bonding agents in steel-belted radial tires, catalysts for the chemical and petroleum industries, drying agents for paint, electrodes for rechargeable batteries, glass decolorizers, ground coat frits for porcelain enamels, magnetic recording media, and pigments. Most of these applications are considered to be dissipative—the cobalt represents an important but very minor constituent of the final product, which is widely distributed during use. This makes cobalt reclamation or recycling impractical or impossible. Two exceptions are the use of cobalt in catalysts and rechargeable batteries, which are products that are recycled.

Cobalt catalysts are used to improve the reaction rates of various processes in the chemical and petroleum industries. In 1998, the top two applications that used cobalt catalysts were the hydroprocessing of petroleum and the production of terephthalic acid (TPA) and dimethyl terephthalate (DMT), which were intermediate compounds in the production of polyester (Field, 1999).

Rechargeable batteries are a relatively new and rapidly growing application for cobalt. In 1998, three types of rechargeable batteries contained cobalt—lithium-ion (Li-ion), nickel-cadmium (NiCd), and nickel-metal hydride (NiMH). The percentages by weight of cobalt in the electrodes in each of these battery types were as follows: Li-ion, 0 to 50 percent of the cathode; NiCd, 3 to 10 percent of the cathode; and NiMH, 3 to 10 percent of the cathode and 3 to 15 percent of the anode (Dominey, 1997). These batteries were either large wet industrial batteries or small sealed dry-cell consumer batteries.

In 1998, the United States was the world's largest consumer of cobalt (Burstow, 2000). Compared with total world cobalt consumption, the United States consumed proportionally more cobalt to make superalloys but less to make batteries (Clark, 1996; Dominey, 1997). Even though as much as 70 percent of cobalt-bearing batteries were made in Asia, a significant percentage of these batteries would have been sent to the United States to be used by U.S. consumers (Dominey, 1997).

Figures 2 and 3 show trends in U.S. consumption of cobalt by various industry sectors since 1978. In figure 2, the cyclic nature of commercial aircraft production is shown in the pattern of cobalt consumption to make superalloys (Schenk, 1998). Figure 3 shows a decrease in cobalt consumption by various industries in the late 1970s to early 1980s. This change in consumption was the result of efforts to conserve cobalt and to find substitutes following a rapid price increase in the late 1970s and recession in the early
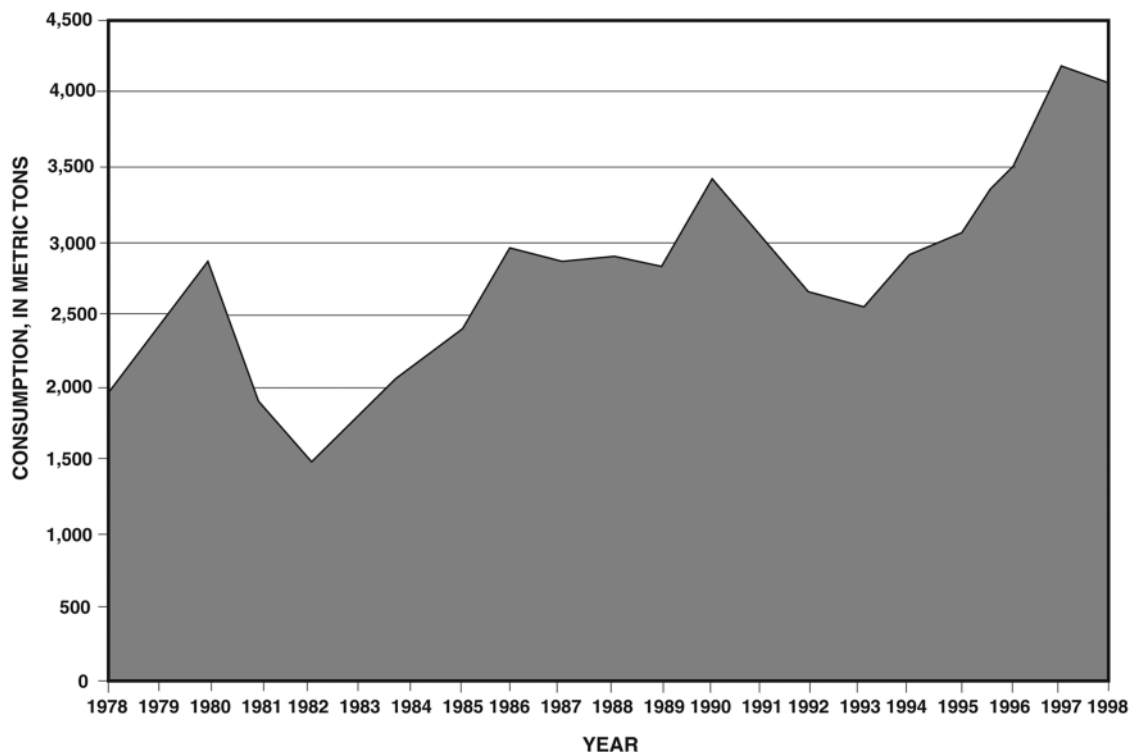

Figure 2. U.S. cobalt consumption in superalloys from 1978 through 1998. Values are in metric tons of contained cobalt.
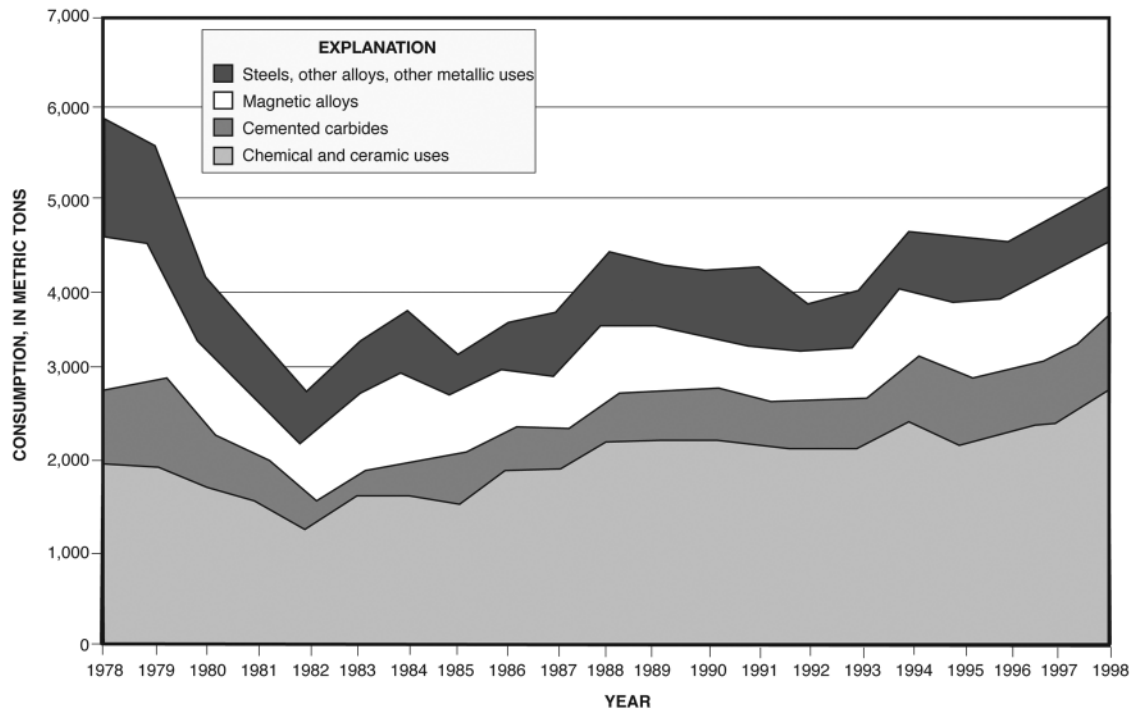
Figure 3. U.S. cobalt consumption, by end-use sector, excluding superalloys, from 1978 through 1998. Values are in metric tons of contained cobalt.

1980s (Shedd, 1999). Figure 3 also shows increasing cobalt consumption for cemented carbides and chemical applications beginning in 1983.

In the late 1970s, approximately one-quarter of U.S. cobalt consumption was for chemical uses, and three-quarters was for metallurgical uses. By the early 1990s, the proportion of U.S. cobalt consumption for chemical uses had grown to approximately one-third of total U.S. consumption. Although some chemical uses of cobalt are recycled, many are dissipative. As a result, an increase in cobalt consumption in chemical uses has the potential to decrease the proportion of cobalt consumption available for recycling.

PRICES

The price of cobalt metal has a significant influence on its recycling rate. Higher prices for cobalt encourage recycling and metal recovery; lower prices do not. Since the late 1970s, free market prices for cobalt have varied considerably (Shedd, 1999). During the 1990s, the U.S. spot price for cobalt cathode (minimum of 99.8 percent cobalt), as reported in Platt's Metals Week, fluctuated widely between a low of $7.50 per pound ($16.50 per kilogram) and a high of $35 per pound ($77 per kilogram) (figure 4). Although this price varied significantly during the course of each year, the annual average price has trended downward since 1995. During 1998, the U.S. spot cathode price decreased to a low of $10 per pound ($22 per kilogram) in mid-December from a high of $26 per pound ($57 per kilogram) in early January.

SOURCES OF COBALT SCRAP

Sources of cobalt scrap are key features of the U.S. cobalt materials flow shown in figure 1. Domestic scrap originates during manufacturing and following use of products in the United States. Scrap generated in foreign countries can enter the United States as imports.

OLD SCRAP GENERATED

Old scrap consists of cobalt-bearing products that are no longer being used. Some examples are used turbine blades and other parts removed from jet engines, spent rechargeable batteries, spent catalysts, used cemented carbide cutting tools, and magnets removed from consumer or industrial equipment. To estimate the amount of cobalt that becomes available from old scrap (termed "old scrap generated") in 1998, the following approach was used. For each cobalt-consuming industry in the United States, the average number of years the products would be in use was estimated. These product lifetimes were subtracted from 1998 to determine the year in which the product would have been manufactured. The amount of cobalt in the products was based on the amount of cobalt consumed by that industry sector during the year of manufacture minus the amount of cobalt that ended up as waste materials or new scrap. The amount of cobalt consumed by each industry sector in the year the products were manufactured was based on information collected by the U.S. Bureau of Mines or the U.S. Geological Survey. The percentage of cobalt consumed by each sector that ended up in final products was derived from the National Research Council (1983).
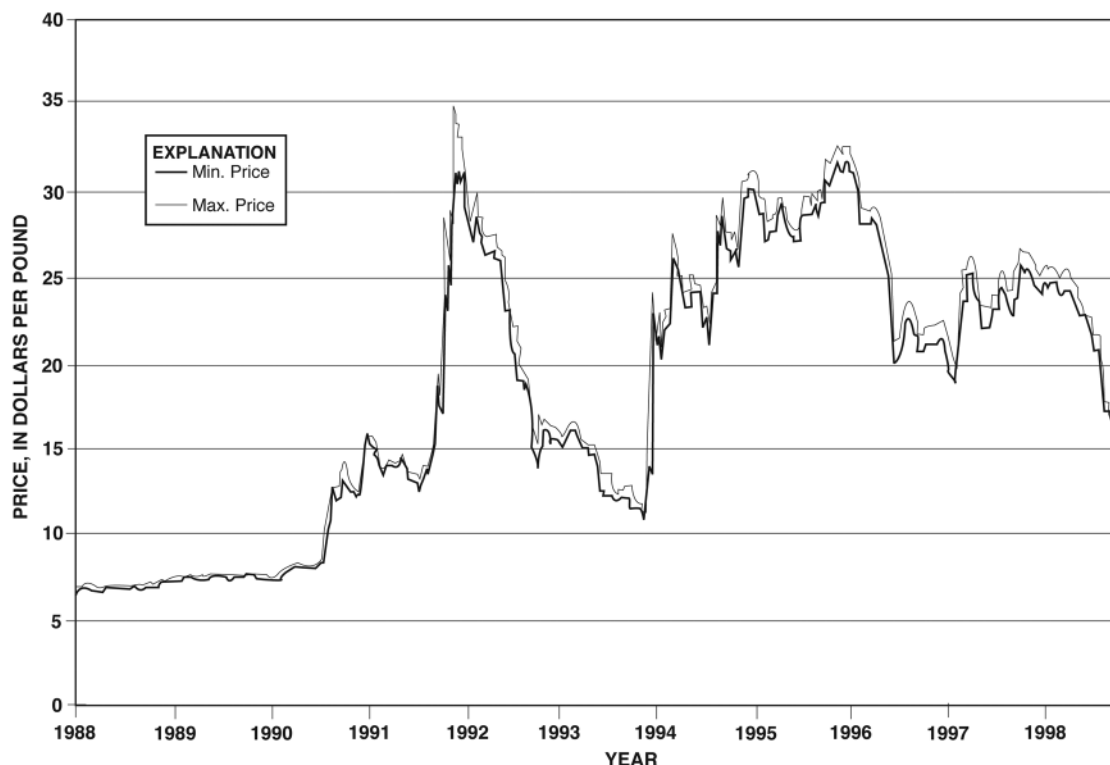
Figure 4. U.S. spot cobalt cathode prices from 1988 through 1998. (Source: Platt's Metals Week)

This method of estimating old scrap generated is based entirely on cobalt consumed to make products in the United States and does not take into account the amount of cobalt in products imported into the country or exported out of the country. Although the net trade of cobalt in products could significantly alter the estimation of old scrap generated, the amount of cobalt in imported and exported products would be very difficult to quantify. Such items as magnets and rechargeable batteries are present in a multitude of products, instrumentation, and equipment used by consumers, industry, and the military and come in a multitude of sizes and various chemical compositions, some of which contain cobalt and some of which do not. Because of the lack of adequate information from which to make reliable estimates, no attempt was made to estimate the net trade of cobalt in products for this study.

As shown in figure 1 and table 1, 3,500 metric tons (t) of cobalt was contained in products that theoretically became available for recycling in 1998.

NEW SCRAP

New scrap is generated during the manufacture of alloys and other cobalt-bearing materials and products. It is often divided into "hard" and "soft" scrap. Hard scrap is in the form of solid pieces, such as subspecification alloy or cemented carbide parts or excess alloy generated during casting operations or removed during pressing and forging operations. Soft scrap is finely divided material. Examples include grinding sludges, swarf, turnings generated during

machining of steel and alloy parts, baghouse dust from steel and alloy manufacturing, and loose powders generated from powder metallurgical processes.

The superalloy industry typically generates large quantities of new scrap. The buy-to-fly ratio, which is the weight of metal purchased versus the weight of the finished parts, provides a measure of the amount of scrap generated. Depending on the part being made, these ratios can range from less than 5 to 1 to greater than 20 to 1. In 1998, the average buy-to-fly ratio was about 7 to 1; this means that for every kilogram of aircraft engine parts produced, 7 kilograms (kg) of metal was purchased and 6 kg of scrap was generated (Lane, 1998; Schenk, 1998). New superalloy scrap can be in the form of solids, turnings, or grindings. By volume, turnings are the largest quantity generated (Lane, 1998).

New scrap is also generated during the casting of corrosion-resistant alloys. In this industry sector, for every kilogram of alloy poured, only 0.4 to 0.6 kg of usable casting is produced. In other words, 40 to 60 percent of the melt becomes new scrap, which would be either recycled in-house or sold to be recycled elsewhere. The number of buyers may be limited, however, by the composition of the scrap. Certain elements that may be present in cobalt-base corrosion-resistant alloys, such as copper and tungsten, are not tolerated in many other cobalt-bearing alloys (Spence and Stickle, 2002).

For the purpose of this study, new scrap does not include home scrap, which is generated and consumed

within a single plant. Quantities of new scrap and home scrap generated by U.S. producers of cobalt metal powder and chemicals were estimated from information in the U.S. Environmental Protection Agency's Toxics Release Inventory (TRI). Reports that provided data on releases, transfers, and recycling of cobalt compounds were generated by using the toxic releases query form at URL http://www.epa.gov/enviro/html/tris/tris_query.html. Reported data from individual plants were summed to estimate U.S. totals. In 1998, the cobalt metal powder and chemical producers recycled approximately 20 t of cobalt in new scrap inhouse (identified as home scrap in figure 1), transferred approximately 30 t of cobalt in new scrap to other plants to be recycled, and released approximately 15 t of cobalt as processing losses to the air, land, or water.

Cobalt in processing losses, new scrap generated, and products from U.S. industry sectors that produced alloys, parts, and other cobalt-bearing products are shown on the right-hand side of figure 1. The amount of cobalt lost during fabrication was derived from TRI releases. In 1998, approximately 350 t of cobalt was released as processing losses. This equaled 3 percent of the apparent supply of cobalt used for fabrication. The amount of cobalt in new scrap generated in 1998 was calculated by adding the estimates for cobalt in new scrap consumed and new scrap exports.

SCRAP IMPORTS

U.S. trade statistics are classified under the Harmonized Tariff Schedule of the United States Annotated (HTSA). The HTSA provides statistical categories and the applicable tariff rates for all merchandise imported into the United States. It is based on the international Harmonized System, which is the global classification system that is used to describe most world trade in goods.

The U.S. Census Bureau reported gross weight and customs value of imports of cobalt waste and scrap under HTSA category 8105.10.9000. The cobalt content of these imports was estimated as follows: for each month, for each country of origin and port of entry, the gross weight was multiplied by the unit value divided by Platt's Metals Week's monthly average spot price for cobalt metal.

In 1998, the United States imported an estimated 250 t of cobalt in cobalt-bearing scrap under HTSA category 8105.10.9000. On the basis of gross weight, most of this scrap originated from Belgium, Canada, Finland, France, Germany, Japan, the Netherlands, and the United Kingdom.

Additional cobalt was likely to have been imported in scrap listed under other HTSA categories. One example would be superalloy scrap imported under the HTSA category for nickel waste and scrap (7503.00.0000). The total estimated cobalt content of imported scrap was increased to 600 t to include an estimate for the cobalt content of these other types of scrap.

Specific information on the type of scrap imported was not available. Industry sources confirmed that much of the imported superalloy scrap is in the form of turnings. The amounts of new and old scrap imported were estimated by using the new-scrap-to-old-scrap ratio of 50:50 that was calculated for U.S. consumption.

DISPOSITION OF COBALT SCRAP

Cobalt-bearing scrap can be consumed (by recycling, processing to recover the cobalt, or downgrading), stocked, exported, or disposed of.

SCRAP CONSUMPTION (RECYCLING AND RECOVERY)

Estimates of new and old scrap consumption were made by using information from various sources, which included data reported to the U.S. Geological Survey, personal communications with industry representatives, and published reports. In 1998, U.S. industry consumed an estimated 1,700 t of new scrap and 1,700 t of old scrap. This resulted in a new-to-old-scrap ratio of 50:50 (table 1).

Recycled cobalt includes cobalt in recycled scrap where the cobalt is not necessarily wanted, but is tolerated. This is referred to as "downgraded cobalt." Downgrading happens when cobalt-bearing scrap is recycled to a steel or to an alloy in which the cobalt is diluted to a residual or background level to a point where its unique properties are not fully utilized. Cobalt then effectively acts as a substitute for iron, nickel, or other alloying metals. For the purposes of this study, downgraded cobalt was counted as scrap consumption rather than as a loss (see definition for recycling in the Appendix).

SCRAP EXPORTS

The U.S. Census Bureau combined exports of cobalt waste and scrap with those of cobalt metal under HTSA category 8105.10.0000. The following procedure was used to distinguish cobalt scrap from cobalt metal. Data were available on a monthly basis for individual countries of destination and ports of departure. For each month, a minimum price for cobalt metal was determined from a comparison of prices published in Platt's Metals Week and Metal Bulletin and unit values of National Defense Stockpile (NDS) cobalt awarded by the Defense National Stockpile Center. Exports with unit values above this minimum were considered to be cobalt metal, and exports with unit values below this minimum were considered to be cobalt scrap. The cobalt content of the cobalt metal exports was assumed to be nearly 100 percent, or roughly equal to the gross weight. The cobalt content of the scrap exports was estimated as follows: for each month, for each country of destination and port of departure, the unit value in dollars per pound was calculated by dividing the free-alongside-ship value by the gross weight. The gross weight was then multiplied by the unit value divided by Platt's Metals Week's monthly average spot price for cobalt metal.

In 1998, the United States exported an estimated 200 t of cobalt in cobalt-bearing scrap under HTSA category 8105.10.0000. On the basis of gross weight, most of this scrap was sent to Belgium, Canada, China (which included Hong Kong), Finland, France, Japan, the Netherlands, and the United Kingdom. The remainder was sent to 14 other countries.

Additional cobalt was likely to have been exported in scrap listed under other HTSA categories. Following discussions with major foreign refiners of U.S. cobalt-bearing scrap and an analysis of exports of nickel waste and scrap under HTSA category 7503.00.0000, the total estimated cobalt content of exported scrap was increased to 1,800 t, and the new-to-old-scrap ratio was estimated to be 50:50.

UNRECOVERED OLD SCRAP

In figure 1 and table 1, unrecovered old scrap represents cobalt in scrap that has not been recycled either in the United States or elsewhere. The amount of cobalt recycled depends on the type of scrap and the price of cobalt (De Jonghe, 1996, p. 9-12). An estimate of the amount of cobalt in unrecovered old scrap was derived by subtracting old scrap consumption and old scrap exports from old scrap supply. The following factors could lead to overestimating the amount of unrecovered old scrap: an overestimate of the amount of old scrap generated that results from products that were still being used in 1998 or that had been exported prior to 1998, double counting between old scrap generated and old scrap imports that results from imported obsolete products that had been manufactured in the United States prior to 1998, and underestimates of old scrap consumed or exported.

OLD SCRAP RECYCLING EFFICIENCY

Recycling efficiency shows the relation between the amount of cobalt in used products theoretically available for recycling and the amount that is recovered or recycled. By definition, this relation is the amount of cobalt in old scrap consumed and exported divided by the amount of cobalt in old scrap generated, imported, and released from stocks. The recycling efficiency for old scrap calculated for 1998 was 68 percent (table 1). Factors that would lead to underestimating old scrap recycling efficiency are as follows: underestimates of the amounts of cobalt-bearing scrap consumed or exported and overestimates of old scrap supply.

INFRASTRUCTURE OF COBALT SCRAP INDUSTRY

Although the United States is a major cobalt consumer, it has not mined or refined a significant amount of cobalt for many years. In 1998, only negligible amounts of byproduct cobalt were produced as intermediate products from U.S. mining operations. U.S. cobalt supply comprised imports, releases from industry stocks, sales of excess cobalt metal from the NDS, and the recycling of cobalt-bearing scrap.

The collection and processing of cobalt-bearing scrap depended on several factors, such as the type, quality, and volume of the scrap. A wide variety of collecting, sorting, preliminary processing, and recycling or metal reclamation systems was used. Some scrap was handled by dealers, brokers, or waste management companies. Some scrap went through other collection, sorting, and processing routes. Examples of collecting, sorting, and preliminary processing routes for two types of scrap—alloy scrap and batteries—are described below. Following collection, sorting, and preliminary processing, most of the cobalt-bearing scrap was processed and/or consumed in the United States. Examples of scrap processing technologies used in the United States are described in the section "Processing of Cobalt Scrap." The remaining cobalt-bearing scrap was exported to foreign smelters, refiners, processors, or consumers either directly or following some initial processing.

ALLOY SCRAP

This category includes new and old scrap of the following types: corrosion- and wear-resistant alloys, magnetic alloys, specialty steels, superalloys, and other cobalt-bearing alloys. Scrap metal processors collect, sort, and process metal and alloy scrap and then return it to scrap consumers for melting (Institute of Scrap Recycling Industries, Inc., 1996, p. 15). Solid pieces of new and old metal and alloy scrap are first hand sorted by alloy type. Skilled sorters do a preliminary sort on the basis of shape (object recognition), color, and weight of the scrap items. If necessary, the items are then tested with one or more of the following methods: response to a magnet, analysis of the spark pattern generated when the alloy is ground on an abrasive wheel, or chemical or physical analysis by various methods (Newell and others, 1982, p. 1–2; Riley, 1990, p. 576–577). Once the solids have been sorted by alloy type, any attachments must be removed and all assemblies must be dismantled. Additional processing, such as washing, degreasing, chemical milling, shot blasting, pickling, and cutting to size, depends on the condition of the scrap and the customer's requirements (Meschter, 1990; Monico Alloys, Inc., undated).

Turnings represent the largest quantity, by volume, of superalloy scrap generated. Scrap processors collect these turnings; qualitatively verify their chemical purity to remove materials that would contaminate a superalloy melt; crush the turnings into chips; quantitatively assay the chips; clean residual cutting fluids and dirt from the chips by kiln processing, detergent cleaning, or solvent cleaning; sample and analyze the scrap to certify that it meets certain chemical specifications; prepare homogeneous lots if desired; densify the chips if desired; and then package the scrap for return to the superalloy melter (Lane, 1998).

Turbine engine parts from dismantled military aircraft are an example of cobalt-bearing old scrap. The Defense Reutilization and Marketing Service (DRMS) is the U.S.

Department of Defense (DOD) agency that disposes of excess property received from the military services. The DRMS first offers excess military property for reuse within the DOD, transfers it to other Federal agencies, or donates it to State and local governments and certain nonprofit organizations. Property that is not reused, transferred, or donated is offered for sale to private companies and individuals (Defense Reutilization and Marketing Service, undated). The DRMS periodically holds sealed bid sales with offers of high-temperature alloy scrap in the form of turbine engine parts. Scrap metal processors are potential buyers of this scrap.

BATTERIES

The use of rechargeable batteries and the subsequent recycling of spent batteries are motivated by the desire to conserve natural resources, to reclaim valuable metals, and to reduce the levels of hazardous metals released into the environment. Battery scrap can be classified into the following broad categories: manufacturing wastes, large wet industrial batteries, and small sealed dry-cell consumer batteries. Manufacturing scrap is generally limited in terms of the number of sources and battery chemistries at each source, a fact that facilitates collection for recycling. In contrast, industrial batteries and, to an even greater extent, consumer batteries become widely dispersed when put into products and distributed to end users. As a result, their collection and sorting by battery chemistry is one of the challenges to achieving a high recycling rate.

In 1998, U.S. collection programs for spent rechargeable batteries were coordinated by a wide variety of entities. "Charge Up to Recycle!" was a public education and battery recycling program. This program had been developed by the Portable Rechargeable Battery Association and was administered by Rechargeable Battery Recycling Corp. (RBRC), which was an international nonprofit public service organization funded by manufacturers and marketers of portable rechargeable batteries and products. In 1998, the RBRC program promoted and implemented the collection of spent NiCd batteries from households and businesses. These batteries were collected at an established network of more than 20,000 retail outlets, 300 community collection centers, and 1,000 businesses and public agencies. Batteries collected under the RBRC program were sent to The International Metals Reclamation Co. (INMETCO) for metal recovery. In early 2000, RBRC announced that it planned to expand its collection program to include Li-ion, NiMH, and small sealed lead rechargeable batteries (England, 1999; Rechargeable Battery Recycling Corp., 2000).

Most NiCd battery manufacturers maintained battery take-back programs and developed specific arrangements with metal recovery facilities to process the batteries (Morrow and Keating, 1999, p. 27, 34). Sony Electronics

Inc. had a take-back program for their Li-ion batteries. In 1998, approximately 1 to 2 t of spent Li-ion batteries was collected by Sony and sent to the company's Dothan, Ala., facility, where they were calcined to remove any residual charge. The calcined batteries were then sent to a refiner or processor to recover the cobalt (Smith, 1999).

By 1998, many manufacturers of NiCd battery-powered consumer products, such as Black & Decker Corp. and Motorola, Inc., had battery take-back programs and were participating in the RBRC program. End-users of industrial NiCd batteries generally had arrangements with their suppliers to return spent batteries for recycling. Some municipalities, armed services, and government agencies also ran battery collection programs (Biagoni, 1999; Morrow and Keating, 1999, p. 28, 34).

INMETCO collected consumer and industrial NiCd batteries under several programs that were developed to serve the needs of cellular phone companies, hospitals, police departments, libraries, municipalities, local communities, and lead smelters that received spent NiCd batteries instead of spent lead batteries. INMETCO collected consumer batteries via a mail-back program, a prepaid container program, the RBRC program, a small package program, and "milk runs" (see Appendix). INMETCO had its own industrial battery collection program and received industrial batteries collected by waste management companies. In addition to batteries from the United States, INMETCO received batteries from Canada, Europe, and South America and battery manufacturing scrap from the United States and elsewhere (Hanewald, McComas, and Liotta, 1999, p. 61–63).

Spent rechargeable batteries collected under various programs were either shipped directly to a metal recovery facility in the United States or elsewhere or sent to a battery processor, also referred to as a "battery breaker" or "secondary battery recycler." The responsibility of the battery processor was to sort the batteries by chemistry and then to send them to the appropriate recovery facilities. In some cases, the processor also dismantled the batteries, separated their components, treated the electrolytes, and/or stored batteries or electrodes prior to shipping them to recovery facilities (Morrow and Keating, 1999, p. 29-30). Kinsbursky Brothers, Inc., of Anaheim, Calif., is an example of a battery processor. In 1998, Kinsbursky Brothers was permitted to process the following cobalt-bearing battery types: Li-ion, NiCd, and NiMH (Coy, 1999).

PROCESSING OF COBALT SCRAP

A wide variety of technologies are used to process cobalt-bearing scrap in the United States. The following are brief descriptions of some of the technologies in use in 1998 for various types of this scrap.

ALLOY SCRAP

Sorting and processing activities performed by scrap metal processors were described previously in the section "Infrastructure of Cobalt Scrap Industry, Alloy Scrap." In some cases, alloy scrap required remelting before it could be reused. Greenville Metals, Inc., of Transfer, Pa., was a specialty alloy producer that offered scrap conversion services. These services entailed remelting customer alloy scrap in an electric arc furnace, adjusting its chemical composition, and then returning the scrap to the customer as an alloy in the form of shot, pigs, or ingots with a certified uniform chemistry. Greenville Metals was able to treat various forms of alloy scrap, such as grindings, turnings, and other low-grade scrap (Greenville Metals, Inc., undated a–d). Additional companies that treated alloy grindings and dusts by using hydrometallurgical or pyrometallurgical processes are described in the section "Mixed Scrap Feeds."

BATTERY SCRAP

When recycling cobalt-bearing batteries, certain metals, such as the cadmium in NiCd batteries and the aluminum in Li-ion batteries, were first recovered or separated from the scrap to facilitate processing the remaining scrap. The processes used by INMETCO and OMG Americas, Inc., to recycle battery scrap are described in the section "Mixed Scrap Feeds."

CEMENTED CARBIDE SCRAP

Many processes for recycling cemented carbide scrap were available for use during 1998. The processes could be generally classified as either direct or indirect recycling. In direct recycling, the cemented carbides were disaggregated, and the resulting powder of tungsten carbide and cobalt was more or less ready to be used to make new cemented carbide parts. Examples of direct recycling processes include bloating, the coldstream process, leach milling with partial cobalt removal, and the zinc process. In indirect recycling processes, the individual components were recovered and purified separately by using chemical methods. Examples of indirect recycling processes included chlorination, leach milling with total cobalt removal, nitrate and/or nitrate-carbonate fusion, and oxidation-sodium hydroxide leaching. In general, the chemical processes had advantages, such as the ability to remove impurities, but tended to have higher costs, higher energy consumption, lower yields, and more waste products than the direct recycling methods. A balance between using indirect chemical recycling and direct recycling processes allowed industry to recycle soft and hard, contaminated and clean cemented carbide scrap; to reduce the overall impurity levels in reclaimed materials; and to reduce recycling costs (Kieffer, 1982; Kieffer and Lassner, 1987; Stjernberg and Johnson, 1998; Gries, 1999; Oakes, 1999).

In the United States, an estimated 35 percent of cemented carbide scrap was recycled by using indirect chemical processes, 25 percent was recycled by using the zinc process, and 5 percent was recycled by using other processes. The remaining 35 percent was not recycled (Stjernberg and Johnson, 1998).

Osram Sylvania Inc. was an example of one U.S. company that used a chemical process to recycle cemented carbide scrap. Tungsten production at Osram's Towanda, Pa., plant was from ore concentrates and tungsten-bearing scrap. The concentrates and oxidized scrap were leached with sodium hydroxide to produce a sodium tungstate solution, which was filtered to remove byproduct sludge that contained cobalt and other metals recovered from the scrap. The sludge was treated chemically to separate the metals. Once separated, the cobalt was converted to cobaltic oxide, which was then reduced by hydrogen to cobalt metal powder. In addition to cemented carbide scrap, Osram's chemical process was able to treat other cobalt-bearing scrap, such as alloys and catalysts (GTE Products Corp., undated, p. 8–9, 16–17; Osram Sylvania Inc., undated).

In 1998, OMG Americas expanded its Apex hydrometallurgical plant in Saint George, Utah, to recycle hard and soft cemented carbide scrap. Cobalt compounds and ammonium paratungstate were the products of this recycling (Magdics, 1997, p. 17; 1998, p. 19, 22, 31; OM Group, Inc., 1999, p. 3). More information on the Apex plant is provided in the section "Mixed Scrap Feeds."

Some U.S. tungsten processors and cemented carbide producers used the zinc process to recycle hard cemented carbide scrap. The scrap was first sorted by grade and cleaned to remove any brazing or impurities and then immersed in molten zinc in the presence of argon gas. The molten zinc reacted with the cobalt binder, which caused the scrap to expand. The zinc was removed by vacuum distillation and left behind a tungsten carbide and cobalt material, which was crushed, milled, and blended. Following chemical analysis and carbon adjustment, the reclaimed powder was then ready to press into new cemented carbide parts (Kieffer, 1982; Stjernberg and Johnson, 1998).

DIAMOND TOOL SCRAP

Small amounts of scrap generated by diamond tool manufacturers were recycled, primarily to recover the diamonds. The recovered cobalt was sent to cobalt processors or refiners. Used tools were either discarded or downgraded to steel (De Jonghe, 1996, p. 9).

MIXED SCRAP FEEDS

In 1998, an undetermined number of plants in the United States recovered cobalt and other metals from a mix of waste and scrap types. The cobalt-bearing waste and scrap treated by these plants included alloys, battery scrap, cakes,

dusts, filters, grindings, overspray, powders, residues, slags, sludges, slurries, solids, solutions, and spent catalysts from the petroleum and chemical industries. Selected plants, the processes they used, and the types of scrap treated are described in the remainder of this section.

The OMG Americas Apex plant recovered cobalt from a variety of scrap materials, which included alloys, spent Li-ion and NiMH batteries, Li-ion and NiMH battery manufacturing scrap, spent catalysts from the petroleum and polyester fiber manufacturing industries, residues, and other cobalt-bearing materials. The general process for treating scrap at Apex was as follows: leaching, removal of impurities, solvent extraction, precipitating the cobalt as carbonate, and then drying the carbonate or calcining it to oxide. Torched spent battery scrap was shredded, screened, and then magnetically separated before processing. Li-ion battery electrode scrap was shredded, calcined, and then screened to separate aluminum from frit-grade oxide without hydrometallurgical treatment. Products from the Apex plant included cobalt carbonate, cobalt nitrate, cobalt oxide, cobalt sulfate solution, frit-grade oxide, lithium-cobalt dioxide, and custom-produced specialty chemicals. The plant had the capacity to recycle from approximately 450 to 900 metric tons per year (t/yr) of cobalt (Magdics, 1997, p. 17, 19–20, 25–29; 1998, p. 16, 19, 22, 24, 26–31).

The INMETCO plant in Ellwood City, Pa., used a high temperature metal recovery process to treat a wide range of nickel-, chromium-, and iron-bearing wastes, which included spent batteries, spent catalysts from oil refining and chemical manufacturing, and wastes from the plating, specialty steel, superalloy, and surface-finishing industries in the form of cakes, dusts, filters, grindings, mill scale, sludges, solutions, and swarf. Cobalt-bearing batteries accepted by INMETCO included Li-ion, NiCd, and NiMH. Some of the other materials processed by INMETCO also contained minor amounts of cobalt. In general, INMETCO accepted solid wastes with less than 2 percent cobalt on a dry-weight basis and liquid wastes with less than 1,800 milligrams per liter cobalt.

Spent NiCd batteries were first treated in INMETCO's cadmium recovery furnace to separate cadmium from the other metals present, which were primarily nickel and iron. At INMETCO's main metal recovery plant, solid wastes were blended with carbon and pelletized by using either liquid wastes or water. The pellets, spent catalysts, and shredded nickel and iron from the batteries were reduced in a rotary hearth furnace and then fed into a submerged electric arc furnace where they were smelted to extract the metals. The molten metal was cast into pigs, which were used as remelt alloy by the stainless steel industry. The remelt alloy was primarily iron with from 9 to 19 percent chromium, from 8 to 16 percent nickel, and a maximum of 0.8 percent cobalt.

The INMETCO process recovered 97 percent of the cobalt present in the waste and scrap. In 1991, the Ellwood

City plant had the capacity to treat 50,000 t/yr of raw material to produce 21,000 t of remelt alloy with an average cobalt content of 0.5 percent. This represented approximately 100 t/yr of cobalt. The INMETCO process also generated slag, which was sold as an aggregate, and flue dust and filter cake, which were treated offsite to reclaim lead and zinc (Hanewald, Munson, and Schweyer, 1991, p. 842–846; Hanewald, Onuska, and Schweers, 1995; International Metals Reclamation Co., Inc., The, 1998, p. 1–4, 8–10).

Agmet Metals, Inc., processed filter cakes, filters, grindings, solutions, and spent catalysts that contained primarily cobalt, copper, nickel, and/or zinc. The company produced metal oxide products by calcining these materials in a natural-gas-fired rotary furnace at its plant in Oakwood Village, Ohio. The metal oxides that contained nickel and cobalt were exported to Canadian smelters. Agmet also calcined TPA catalyst sludge, as necessary, to remove organics. The sludge was then toll-leached by Encycle, Inc., at its plant in Corpus Christi, Tex., to remove sodium bromide. The final product of this recycling was a cobalt-manganese powder that was used as a substitute for cobalt oxide by the frit industry (Cassidy, 2000; 2001, p. 2).

The International Metals & Chemicals Group produced a variety of cobalt and nickel compounds from metallic feeds, plating cake and solutions, and spent catalyst at its PPB Technologies plant in Shelby, N.C. The plant processed feed materials by leaching followed by precipitation and filtering (Cassidy, 2001, p. 11).

The Amax Metals Recovery, Inc., plant in Braithwaite, La., processed solutions and sludges that contained cobalt, copper, and nickel in soluble or hydroxide form by using the technology which is described in the section "Spent Catalysts" (Case, Garretson, and Wiewiorowski, 1995, p. 465).

The Osram Sylvania process, which is described in the section "Cemented Carbide Scrap," was able to treat various types of cobalt-bearing scrap, which included alloys and catalysts (Osram Sylvania Inc., undated).

SPENT CATALYSTS

In 1998, two companies operated metal recovery plants in the United States that used spent cobalt-molybdenum and nickel-molybdenum hydroprocessing catalysts as their main source of feed. At Gulf Chemical & Metallurgical Corp.'s Freeport, Tex., plant, spent catalysts and sodium carbonate were roasted in a multiple-hearth furnace to burn off the hydrocarbons and some of the sulfur and to convert the molybdenum, the vanadium, and the remaining sulfur to water-soluble salts. After roasting, the calcine was milled, leached with water to dissolve the molybdenum and vanadium compounds, and then filtered to separate the alumina, cobalt, and nickel solids from the molybdenum and vanadium in solution. The solution was treated to produce molybdenum and vanadium compounds. Depending on its metal content, the filtercake was sold to cement manufacturers or nickel refiners or smelted onsite in Gulf

Chemical's electric arc furnace. If smelted onsite, then the products were high-grade fused alumina for refractory and abrasive applications and an alloy that contained from 37 to 43 percent nickel and from 12 to 17 percent cobalt, which was sold to nickel-cobalt refineries (Gulf Chemical & Metallurgical Corp., 1999; Llanos and Deering, 2000, p. 764–768).

The Amax plant in Braithwaite, was operated under the name CRI-MET and was a partnership between subsidiaries of CRI International, Inc., and Cyprus Amax Minerals Co. This plant used a two-stage pressure-leaching process to recover metals from spent hydroprocessing catalysts. Spent catalysts were milled in a solution of sodium aluminate and sodium hydroxide. The resulting slurry was fed into an autoclave and leached under oxidizing conditions at elevated temperature and pressure to convert the sulfur to sulfate, to oxidize the organic compounds, and to dissolve the molybdenum and vanadium. The autoclaved material was thickened and filtered to separate the liquid from the solids. Molybdenum and vanadium were recovered from the liquid and converted to oxides. The solids, which contained alumina, cobalt, and nickel, were leached a second time at high temperature and pressure with a strong caustic to solubilize aluminum. The nickel-cobalt solids from the second leach were separated, washed, dried, and then shipped to another plant to be calcined. The calcined nickel-cobalt material was then exported to a nickel-cobalt refiner (Crnojevich and others, 1990, p. 463–467; Case and others, 1995, p. 450–453, 461).

Spent hydroprocessing catalysts were also processed by INMETCO and OMG Americas, as described in the section "Mixed Scrap Feeds."

Spent cobalt-manganese catalyst residues from the production of DMT and TPA were sent to cobalt chemical producers, such as OMG Americas and The Hall Chemical Co. These companies either reclaimed the metals by producing cobalt chemicals or upgraded the spent catalysts to new catalysts, which they then returned to the catalyst user (Chemical Marketing Reporter, 1995; Magdics, 1997, p. 19; Hall Chemical Co., The, undated). As described in the section "Mixed Scrap Feeds," Agmet Metals and Encycle converted spent cobalt-manganese catalyst residues into a cobalt-manganese powder that was used as a substitute for cobalt oxide by the frit industry (Cassidy, 2000).

OUTLOOK

The recycling of cobalt-bearing scrap and the recovery of cobalt from scrap materials are well-established practices for a number of reasons. The relatively high price of cobalt compared with that of many other metals and the relatively low price of cobalt-bearing scrap compared with that of primary cobalt make recycling and cobalt recovery economic and desirable. Concern over potential supply disruptions that could result from a high dependence on imports from uncertain supply sources has encouraged recycling and

metal recovery as a way to diversify the sources of raw materials for the production of cobalt and tungsten chemicals, metals, and end products. Additional factors that play a role in promoting cobalt recycling and recovery include environmental regulations; periodic increases in the price of cobalt; the desire to conserve resources and energy, to reduce mining and mineral processing wastes and the costs of disposing of these wastes and of used products, to reduce levels of such hazardous materials as cadmium in NiCd batteries from the environment, and to demonstrate an environmentally responsible image.

World cobalt consumption is expected to continue to increase in coming years. Because most cobalt products can be recycled, the availability of cobalt-bearing scrap is also expected to increase. Future increases in the supply of primary cobalt could negatively impact the amount of cobalt that will be recycled. Cobalt production has been increasing in recent years and is anticipated to continue to increase at a faster rate than that of cobalt demand. The likely response to a growing market surplus would be a generally downward trend in cobalt prices (Shedd, 2001, p. 20.8). The combined effect of a surplus of primary cobalt and low cobalt prices would impact the economics of some recycling and cobalt recovery processes. The prices at which cobalt recycling or recovery would become unprofitable for consumers, processors, and refiners are not available because companies do not want to reveal proprietary information related to their processing costs. One analyst has stated that chemical processors reportedly begin to hold back on using scrap when the price of cobalt is below approximately $15 per pound ($33 per kilogram) but that a major cobalt refiner reportedly has continued to process superalloy scrap when the price of cobalt was as low as $10 per pound ($22 per kilogram) (Hawkins, 1998). Another analyst has stated that there is some evidence that the economics of cobalt recycling and reclamation begin to be impacted when the price of cobalt decreases to $12 per pound ($26 per kilogram) but that the impact is much greater when prices drop to $10 per pound ($22 per kilogram) or lower (Kielty, 2001).

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APPENDIX—DEFINITIONS

apparent consumption. Primary plus secondary production (old scrap) plus imports minus exports plus adjustments for Government and industry stock changes.

apparent supply. Apparent consumption plus consumption of new scrap.

catalyst. A substance that changes the rate of a chemical reaction without being consumed in the reaction.

dissipative use. A use in which the metal is dispersed or scattered, such as paints or fertilizers, making it exceptionally difficult and costly to recycle or recover the metal.

downgraded scrap. Scrap intended for use in making a metal product of lower value than the metal product from which the scrap was derived.

home scrap. Scrap generated as process scrap and consumed in the same plant where generated.

milk run. A routine trip involving stops at many places.

new scrap. Scrap produced during the manufacture of metals and articles for both intermediate and ultimate consumption, including all defective finished or semifinished articles that must be reworked. Examples of new scrap are borings, castings, clippings, drosses, skims, and turnings. New scrap includes scrap generated at facilities that consume old scrap. Included as new scrap is prompt industrial scrap—scrap obtained from a facility separate from the recycling refiner, smelter, or processor. Excluded from new scrap is home scrap that is generated as process scrap and used in the same plant.

new-to-old-scrap ratio. New scrap consumption compared with old scrap consumption, measured in weight and expressed as a percentage of new plus old scrap consumed (for example, 40:60).

old scrap. Scrap including (but not limited to) metal articles that have been discarded after serving a useful purpose. Typical examples of old scrap are electrical wiring, lead-acid batteries, silver from photographic materials, metals from shredded cars and appliances, used aluminum beverage cans, spent catalysts, and tool bits. This is also referred to as postconsumer scrap and may originate from industry or the general public. Expended or obsolete materials used dissipatively, such as paints and fertilizers, are not included.

old scrap generated. Cobalt content of products theoretically becoming obsolete in the United States in the year of consideration, excluding dissipative uses.

old scrap recycling efficiency. Amount of old scrap recovered and reused relative to the amount available to be recovered and reused. Defined as [consumption of old scrap (COS) plus exports of old scrap (OSE)] divided by [old scrap generated (OSG) plus imports of old scrap (OSI) plus a decrease in old scrap stocks (OSS) or minus an increase in old scrap stocks], measured in weight and expressed as a percentage:

$$\frac{COS + OSE}{OSG + OSI + \text{decrease in OSS or} - \text{increase in OSS}} \times 100$$

old scrap supply. Old scrap generated plus old scrap imported plus old scrap stock decrease.

old scrap unrecovered. Old scrap supply minus old scrap consumed minus old scrap exported minus old scrap stock increase.

price. Prices for cobalt scrap are not published. The average price of cobalt metal in 1998 was used to estimate the total value of old scrap consumed. For each type of scrap, a percentage was applied to adjust the relative value of cobalt contained in the scrap to the price of cobalt metal. The total value of net exports of cobalt scrap was derived from trade statistics reported by the U.S. Census Bureau as follows: total estimated value of cobalt scrap exports minus total estimated value of cobalt scrap imports. See "Scrap Exports" and "Scrap Imports" sections of this report for further information on how cobalt scrap trade statistics were estimated.

recycling. Reclamation of a metal in usable form from scrap or waste. This includes recovery as the refined metal or as alloys, mixtures, or compounds that are useful. Examples of reclamation are recovery of alloying metals (or other base metals) in steel, recovery of antimony in battery lead, recovery of copper in copper sulfate, and even the recovery of a metal where it is not desired but can be tolerated—such as tin from tinplate scrap that is incorporated in small quantities (and accepted) in some steels, only because the cost of removing it from tinplate scrap is too high and (or) tin stripping plants are too few. In all cases, what is consumed is the recoverable metal content of scrap.

recycling rate. Fraction of the apparent metal supply that is scrap on an annual basis. It is defined as [consumption of old scrap (COS) plus consumption of new scrap (CNS)] divided by apparent supply (AS), measured in weight and expressed as a percentage:

$$\frac{COS + CNS}{AS} \times 100$$

scrap consumption. Scrap added to the production flow of a metal or metal product.

superalloys. Alloys developed for high-temperature service where relatively high mechanical stress is encountered and where surface stability is frequently required.

swarf. Fine metallic particles and abrasive fragments removed by cutting or grinding tools.